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Mitigating the effects of soil and residue water contents on remotely sensed estimates of crop residue cover

C.S.T. Daughtry *, E.R. Hunt Jr.

USDA-ARS Hydrology and Remote Sensing Laboratory, Bldg 007, Room 104, 10300 Baltimore Ave., Beltsville, Maryland 20705-2350, USA

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Abstract

Crop residues on the soil surface decrease soil erosion and increase soil organic carbon and the management of crop residues is an integral part of many conservation tillage systems. Current methods of measuring residue cover are inadequate for characterizing the spatial variability of residue cover over large fields. The objectives of this research were to determine the effects of water content on the remotely sensed estimates of crop residue cover and to propose a method to mitigate the effects of water content on remotely sensed estimates of crop residue cover. Reflectance spectra of crop residues and soils were measured in the lab over the 400–2400 nm wavelength region. Reflectance of scenes with various residue cover fractions and water contents was simulated using a linear mixture model. Additional spectra of scenes with mixtures of crop residues and soil were also acquired in corn, soybean, and wheat fields with different tillage treatments and different water content conditions. Crop residue cover was linearly related to the cellulose absorption index (CAI), which was defined as the relative intensity of an absorption feature near 2100 nm. Water in the crop residue significantly attenuated CAI and changed the slope of the residue cover vs. CAI relationship. Without an appropriate correction, crop residue covers were underestimated as scene water content increased. Spectral vegetation water indices were poorly related to changes in the water contents of crop residues and soils. A new reflectance ratio water index that used the two bands located on the shoulders of the cellulose absorption feature to estimate scene water conditions was proposed and tested with data from corn, soybean, and wheat fields. The ratio water index was used to describe the changes in the slope of crop residue cover vs. CAI and improve the predictions of crop residue cover. These results indicate that spatial and temporal adjustments in the spectral estimates of crop residue cover are possible. Current mutispectral imaging systems will not provide reliable estimates of crop residue cover when scene water content varies. Hyperspectral data are not required, because the three narrow bands that are used for both CAI and the scene moisture correction could be incorporated in advanced multispectral sensors. Thus, regional surveys of soil conservation practices that affect soil carbon dynamics may be feasible using either advanced multispectral or hyperspectral imaging systems.

Keywords: Crop residue cover; Reflectance spectra; Spectral moisture index; Cellulose absorption index

1. Introduction

Crop residues on the soil surface decrease soil erosion, increase soil organic matter, and improve soil quality (Lal et al., 1999). Thus, management of crop residues is an integral part of many conservation tillage systems. The standard technique for measuring crop residue cover used by the USDA Natural Resources Conservation Service (NRCS) is visual determination of the presence of residue at selected points along a line (Morrison et al., 1993). For corn, at least 500 points were required to determine corn residue cover to within 15% of the mean (Laflen et al., 1981). The line-transect method is designed to assess the average crop residue cover for a field, but not the spatial variability within fields. The Conservation Technology Information Center (CTIC, 2004) has compiled regional assessments of conservation tillage practices for selected counties based on annual roadside surveys of crop residue levels after planting. These surveys are subjective and the techniques vary from county to county (Thoma et al., 2004). Reviews of crop residue measurement techniques illustrate the problems that current techniques have addressing spatial variability of crop residue cover (Corak et al., 1993; Morrison et al., 1995).

* Corresponding author. Tel.: +1 301 504 5015; fax: +1 301 504 8931.
E-mail address: Craig.Daughtry@ars.usda.gov (C.S.T. Daughtry).

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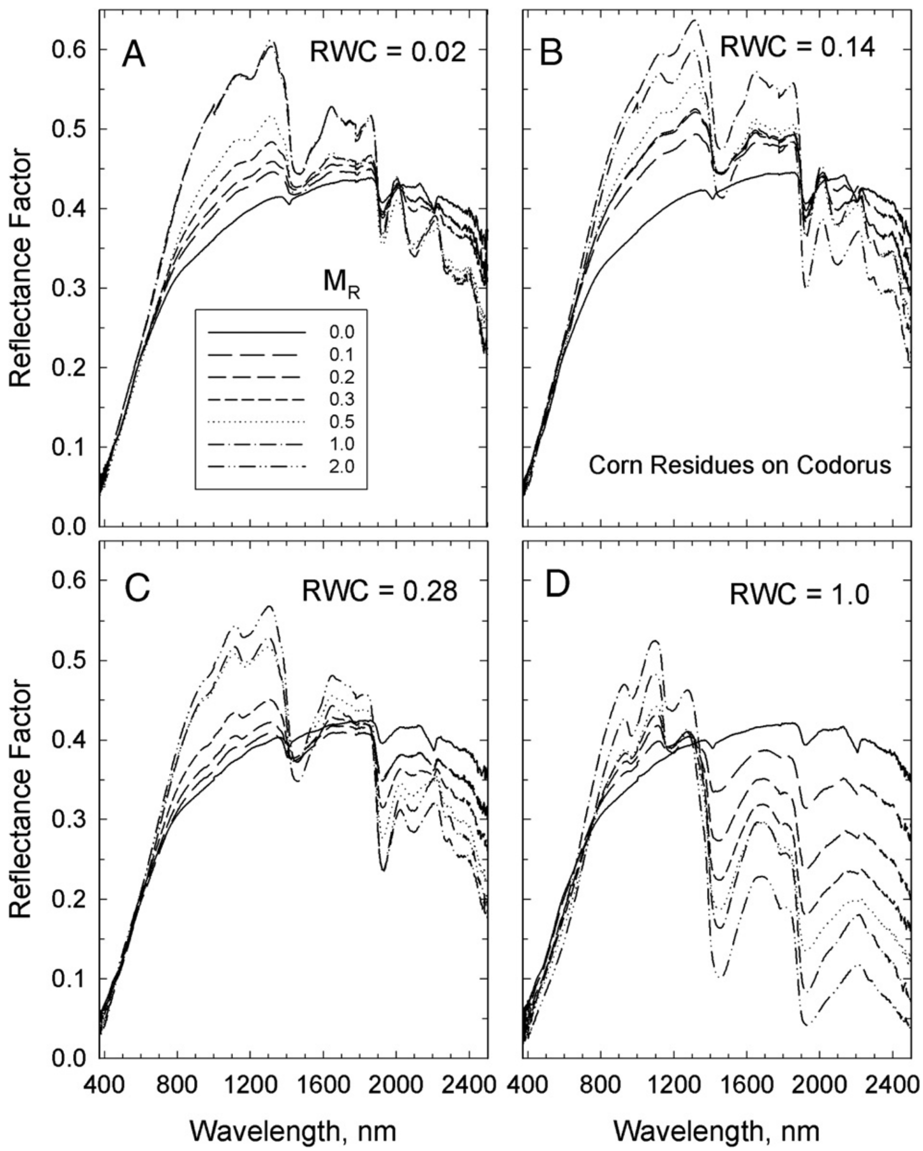

Fig. 1. Reflectance spectra of corn residues at four relative water contents (RWC) on dry Codorus soil. The seven spectra represent mixed scenes with varying amounts of residue mass. $M_R=0$ is bare soil; $M_R=2$ is twice the residue cover required to cover the soil completely.

Traditional remote sensing techniques for assessing crop residue cover and conservation tillage have had mixed success because crop residues and soils are spectrally similar and often differ only in magnitude for visible and near infrared wavelengths (Baird & Baret, 1997; Streck et al., 2002). An alternative approach for discriminating crop residues from soil is based on detecting a broad absorption feature near 2100 nm that appears in all compounds possessing alcoholic –OH groups, such as cellulose (Murray & Williams, 1988). The absorption feature near 2100 nm is clearly evident in the reflectance spectra of the dry crop residues and is absent in the spectra of soils (Elvidge, 1990; Nagler et al., 2000; Streck et al., 2002). The relative intensity of this absorption feature was defined as the cellulose absorption index (CAI; Daughtry et al., 1996a,b). Liquid water also has a strong absorption in this wavelength region (Palmer & Williams, 1974). Water content, age of the residue, and degree of decomposition affected the spectral reflectance and CAI of crop residues (Nagler et al., 2000). Water in the crop residues and soils strongly attenuated the reflectance signal and reduced the accuracy of crop residue cover estimates (Daughtry et al., 2004). Numerous spectral indices using various near infrared and shortwave infrared bands have been correlated with the water content of leaves (e.g., Hunt & Rock, 1989), soils (e.g., Lobell & Asner, 2002; Whiting et al., 2004), and plant canopies (e.g., Hardisky et al., 1983). However, little research has been reported on spectral indices for estimating the water content of crop residues. Annual assessments of the extent of conservation tillage are conducted in the Spring after planting which is often the wettest season of the year. Thus, in order for remote sensing techniques to assess crop residue cover accurately, the spatial variability of soil and crop residue water contents must be determined.

The objectives of this research were to (1) determine the spectral reflectance of mixed scenes (soil + residue) as a function of water content, (2) assess the effects of soil and crop residue

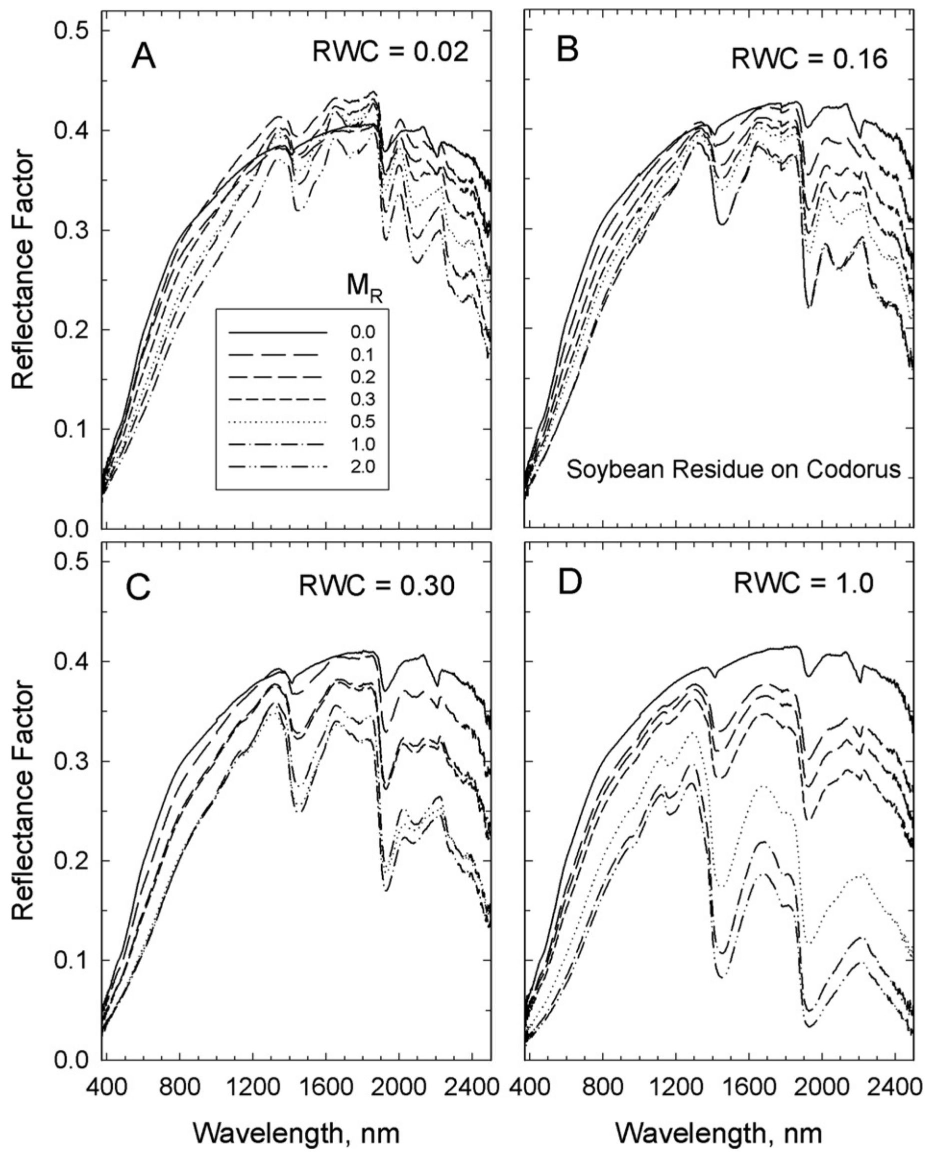

Fig. 2. Reflectance spectra of soybean residues at four relative water contents on dry Codorus soil. The seven spectra represent mixed scenes with varying amounts of residue mass. $M_R = 0$ is bare soil; $M_R = 2$ is twice the residue cover required to cover the soil completely.

water contents on remotely sensed estimates of crop residue cover and (3) propose a method to mitigate the effects of soil and crop residue water contents on remotely sensed estimates of crop residue cover. This research enhances the scientific basis for assessing crop residue cover and soil tillage intensity regionally which may have varying water conditions in the same scene.

2. Materials and methods

2.1. Experiment 1 — Lab spectra of mixed scenes

Reflectance spectra were acquired with a spectroradiometer (FieldSpec Pro, Analytical Spectral Devices, Boulder, CO) over the 400–2400 nm wavelength region at 1 nm intervals. The samples were illuminated by two 300 W quartz–halogen lamps mounted on the arms of a camera copy stand at 50 cm over the sample at a 45° illumination zenith angle. A digital camera and the 18° fore optic of the spectroradiometer were aligned and positioned 90 cm from the sample surface at a 0° view zenith angle which resulted in a 29 cm diameter field of view for the spectroradiometer. The illumination and view angles were chosen to minimize shadowing and to emphasize the fundamental spectral properties of the soils and crop residues. Four spectra of 20 scans each were acquired from samples by rotating the sample tray 90° after each spectrum. A 61-cm square Spectralon reference panel (Labsphere, Inc., North Sutton, NH) was placed in the field of view, illuminated, and measured in the same manner as the samples. Reflectance factors were calculated and corrected for the non-ideal properties of the reference panel as described by Robinson and Biehl (1979).

Codorus (fine-loamy, mixed, active, mesic, Fluvaquentic Dystrudept) topsoil from Beltsville, Maryland was oven-dried at 105 °C for 48 h, crushed to pass a 2-mm screen, and placed to a depth of 1 cm in a 45-cm square sample tray that was painted

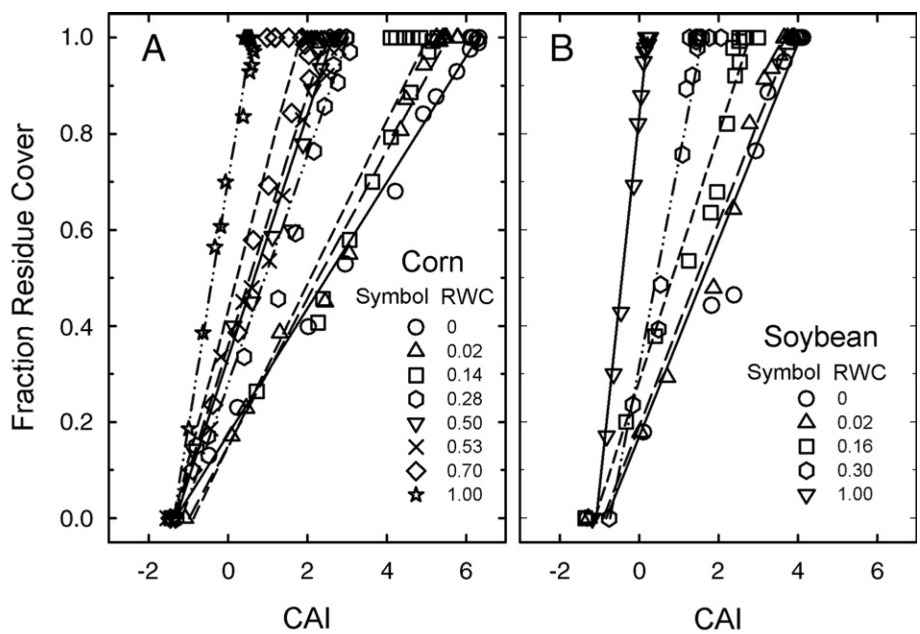

Fig. 3. Residue cover of A) corn and B) soybeans plotted as a function of the cellulose absorption index (CAI) for water contents ranging from dry to saturated. Regression coefficients are presented in Table 1.

flat black. Duplicate trays were prepared. Crop residues of corn (*Zea mays* L.) and soybean (*Glycine max* Merr.) were collected from agricultural fields near Beltsville, Maryland at 8 months after harvest. The crop residues were cut in 10 cm segments and dried at 70 °C for 4 days. The mass of each crop residue (M_R) required to completely cover the tray with one layer was determined. Starting with bare soil, crop residue segments were added to the soil surface in the tray in 0.1 M_R increments to M_R and 0.2 M_R increments to 2 M_R. Spectral reflectance and a digital image of each scene were acquired. For each scene, crop residue cover in the field of view of the spectroradiometer was determined visually using a 140-dot overlay and counting the number of dots intersecting crop residue (Williams, 1979).

The crop residue segments were removed, weighed, placed in mesh bags, immersed in water for 2 h, allowed to drain for 2 h, and re-weighed. Starting with bare soil, the measurement sequence was repeated as wet crop residue segments were added to the soil surface. The crop residue segments were removed from the soil, weighed, allowed to dry slowly at room temperature until approximately 20% of the water mass in the crop residue had evaporated. The residues were placed in large plastic bags and allowed to equilibrate for several hours before the next set of reflectance measurements. The sequence of crop residue drying and spectral measurements was repeated until the crop residues were air-dry. The water content of residues was expressed on a

Table 1
Regression coefficients and standard errors (SE) for corn and soybean residue cover as a function of CAI for various water contents

Residue	RWC	Water g g^{-1}	$B_0 \pm$SE	$B_1 \pm$SE	RMSE	Adj. r^2
Corn	0	0	0.176±0.012	0.129±0.003	0.025	0.995
	0.02	0.06	0.148±0.019	0.155±0.005	0.039	0.988
	0.14	0.61	0.142±0.033	0.160±0.008	0.058	0.970
	0.28	1.23	0.275±0.021	0.228±0.010	0.052	0.979
	0.50	2.18	0.330±0.024	0.253±0.013	0.058	0.971
	0.53	2.28	0.345±0.020	0.245±0.012	0.053	0.975
	0.70	3.03	0.384±0.024	0.301±0.017	0.069	0.967
	1.00	4.26	0.678±0.010	0.487±0.015	0.033	0.990
Soybean	0	0	0.169±0.044	0.203±0.014	0.080	0.951
	0.02	0.04	0.190±0.028	0.213±0.010	0.056	0.976
	0.16	0.29	0.283±0.031	0.254±0.016	0.068	0.959
	0.30	0.54	0.292±0.032	0.470±0.027	0.066	0.964
	1.00	1.86	0.832±0.012	0.771±0.024	0.038	0.989

Measured values and regression lines are plotted in Fig. 3. Residue cover fraction (f_R) was described as $f_R = B_0 + B_1$CAI; where, CAI is the cellulose absorption index and B_0 and B_1 are the linear regression intercept and slope, respectively. RMSE is root mean square error.

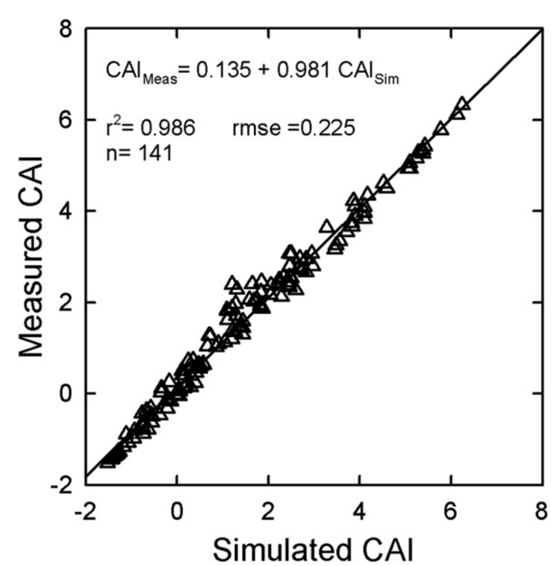

Fig. 4. Measured and simulated CAI values for the corn and soybean scenes described in Figs. 1 and 2. CAI was simulated using a linear mixture model (Eq. (4)).

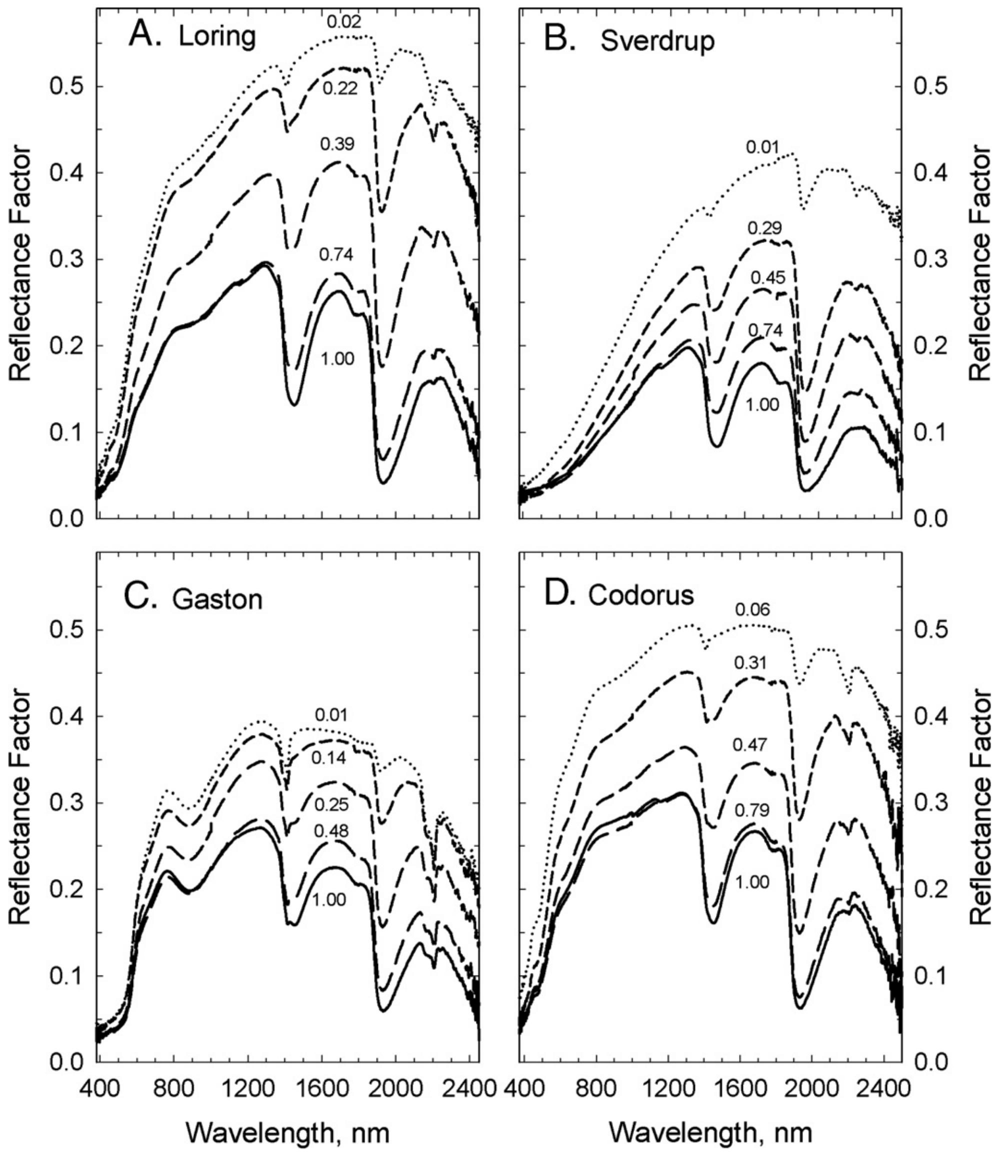

Fig. 5. Reflectance spectra of A) Loring, B) Sverdrup, C) Gaston, and D) Codorus soils for water contents ranging from dry to saturated. Each spectrum is labeled with relative water content. Additional spectra at intermediate RWC values were acquired, but were omitted for clarity.

dry mass basis (g H_2O/g dry mass) and as relative water content (RWC) which was calculated as the water content (weight − oven-dry weight) divided by the maximum water content (saturated weight − oven-dry weight) of each sample (i.e., RWC = 1.0 is saturated and RWC = 0.0 is oven-dry).

2.2. Experiment 2 — Lab spectra of soils

Reflectance spectra were acquired with the ASD spectroradiometer as described for Experiment 1 with minor modifications to accommodate relatively small (< 300 g) samples of soils. The 8° fore optic of the spectroradiometer was positioned 60 cm from the sample surface at a 0° view zenith angle which resulted in a 8.5 cm diameter field of view. A 30-cm square Spectralon reference panel was placed in the field of view, illuminated, and measured in the same manner as the samples. Four diverse agricultural topsoils were selected and included: Loring (fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs) from Como, Mississippi; Sverdrup (sandy, mixed, frigid Typic Hapludolls) from Morris, Minnesota; Gaston (fine, mixed, active, thermic Humic Hapludults) from Salisbury, North Carolina; and the Codorus soil from Experiment 1. Detailed descriptions of these soils are available in Lane and Nearing (1989). Each soil was oven-dried at 105 °C for 48 h, crushed to pass a 2-mm screen, and placed to a depth of 1 cm in 20-cm diameter sample trays. The soils were saturated with water, allowed to drain for 2 h, and reflectance factors were measured. The soils were allowed to dry at room temperature until approximately 15% of the water mass in the soil had evaporated. The soils were placed in plastic bags and allowed to equilibrate for several hours before the next set of reflectance measurements. The sequence of measurements was repeated until the

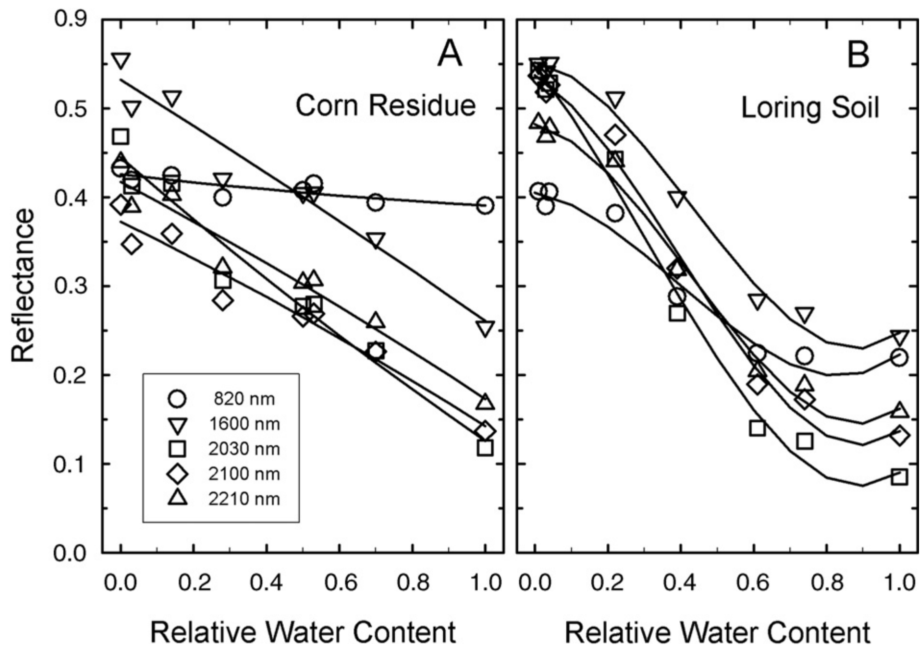

Fig. 6. Reflectance in selected spectral bands plotted as a function of relative water content for A) corn residue and B) Loring soil.

soils were air-dry and then oven-dried. The water content of soils was expressed on a dry mass basis (g H_2O/g dry soil) and as relative water content.

2.3. Experiment 3 — Field spectra

Reflectance spectra of crop residues in production fields near Beltsville, Maryland were acquired with the ASD spectroradiometer. The 18° fore optic of the spectroradiometer and a digital camera were aligned and mounted on a pole at 2.3 m above the soil at a 0° view zenith angle which resulted in a 0.7 m diameter field of view. For calibration, a 46-cm square Spectralon reference panel was placed in the field of view at 0.6 m from the optics, leveled, and measured in the same manner as the scenes. Data were acquired on 20 and 22 May 2002 (data from Daughtry et al., 2004), 10 June 2003, and 1, 2, 9, and 30 June 2004 under clear sky conditions in various corn, soybean, and wheat fields that had different tillage treatments. The fractions of green vegetation, crop residue, and soil in the field of view of the spectroradiometer were determined

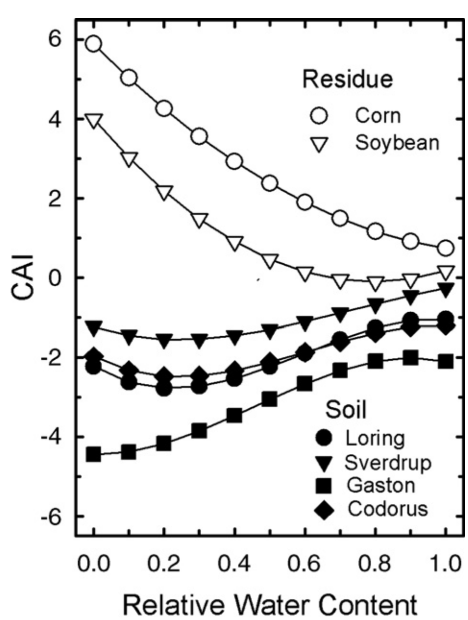

Fig. 7. Changes in crop residue CAI and soil CAI as a function relative water content.

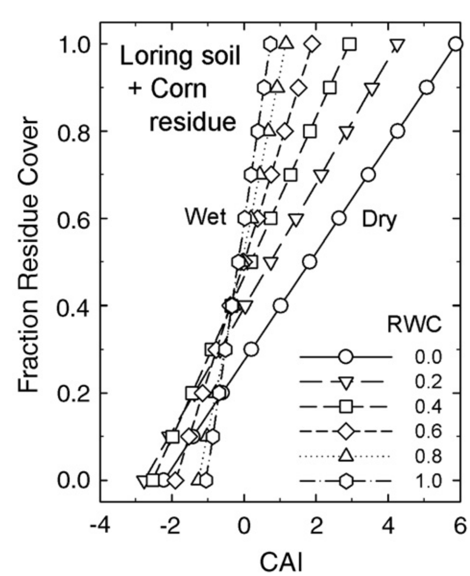

Fig. 8. Residue cover as a function of CAI for simulated scenes of corn residue on Loring soil at a range of relative water contents (RWC).

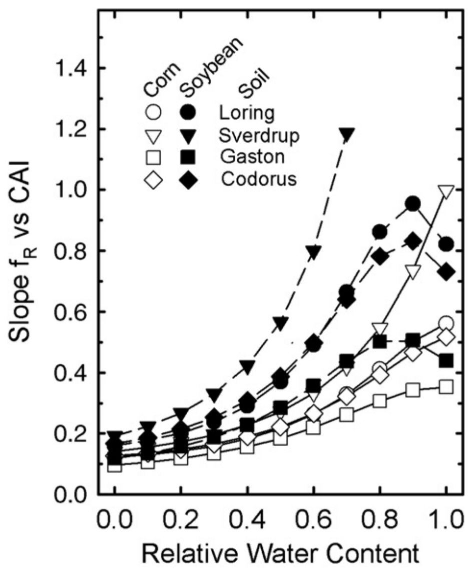

Fig. 9. Slopes of residue cover vs. CAI (slope f_R vs. CAI) for simulated scenes of corn and soybean residues on the four soils at a range of relative water contents (RWC).

visually using a 156-dot overlay on the digital image. Samples of crop residues and the upper 2 cm of soil were acquired on most dates. The soils were dried at 105 °C and the crop residues were dried at 60°. Water contents were expressed on a dry matter basis (g H_2O/g dry soil or residue).

2.4. Data analyses

Mean spectral reflectance factors were calculated and plotted as a function of wavelength, water content, and residue cover. The cellulose absorption index (CAI; Daughtry, 2001), which is an adaptation of the continuum-removal method (Kokaly & Clark, 1999), was calculated as:

$$\mathrm{CAI} = 100(0.5(R_{2.0} + R_{2.2}) - R_{2.1}); \tag{1}$$

where $R_{2.0}$, $R_{2.1}$, and $R_{2.2}$ are the reflectance values in 10-nm bands centered at 2030 nm, 2100 nm, and 2210 nm, respectively.

Two spectral indices designed to assess vegetation water content are the Moisture Stress Index (MSI; Hunt & Rock, 1989);

$$\mathrm{MSI} = R_{1.6}/R_{0.8} \tag{2}$$

and the Normalized Difference Infrared Index (NDII; Hardisky et al., 1983)

$$\mathrm{NDII} = (R_{0.8} - R_{1.6})/(R_{0.8} + R_{1.6}) \tag{3}$$

where, $R_{0.8}$ and $R_{1.6}$ are the reflectance values in 10-nm bands centered at 820 nm and 1600 nm, respectively. Two additional spectral indices were evaluated that used the reflectance difference water index ($R_{2.2}-R_{2.0}$) and the reflectance ratio water index ($R_{2.2}/R_{2.0}$) of the CAI bands in Eq (1). The reflectance of mixed scenes $R_{(M,\lambda)}$ with various proportions of crops residues and soils was simulated using linear combinations of the reflectance factors for crop residues and soils,

$$R_{(M,\lambda)} = R_{(S,\lambda)}(1 - f_R) + R_{(R,\lambda)}(f_R) \tag{4}$$

where $R_{(S,\lambda)}$ and $R_{(R,\lambda)}$ are reflectance factors in waveband λ for soils and crop residues, respectively, f_R is the fraction residue cover that ranged from 0 (100% soil) to 1.0 (100% crop residue), and $(1-f_R)$ is the soil fraction.

3. Results and discussion

3.1. Scene reflectance = f(residue cover, residue water content)

Mean reflectance spectra of corn and soybean residues at four representative relative water contents (RWC) on air-dry Codorus soil are shown in Figs. 1 and 2. For each RWC, the seven spectra represent scenes with different amounts of crop residue cover. As dry corn residue cover increased (Fig. 1A), scene reflectance was unchanged in the visible (400–700 nm), generally increased in the near infrared (700–1400 nm), and decreased in the shortwave infrared (1400–2400 nm). For soybeans, scene reflectance generally decreased as residue cover increased (Fig. 2A). The broad absorption feature near 2100 nm is associated with the –OH bond in the lignin and cellulose molecules (Murray & Williams, 1988) and is clearly evident in crop residue spectra in Figs. 1A and 2A. Elvidge (1990) observed similar absorption bands in the reflectance spectra of dry, intact plant materials. As crop residue cover increased, the cellulose absorption feature near 2100 nm intensified and the CAI value of each scene increased. Even for these contrasting crop residues, CAI was linearly related to crop residue cover (Fig. 3).

Water in the crop residue reduced reflectance across all wavelengths. Major water absorption bands near 1450 and 1960 nm dominated the reflectance spectra at wavelengths > 1300 nm. As water content on the crop residues increased, the reflectance at 2030 nm ($R_{2.0}$) is reduced relative to reflectance at 2200 nm ($R_{2.2}$) and the cellulose–lignin absorption feature near 2100 nm is attenuated (Figs. 1 and 2). Although the absorption feature near 2100 nm was nearly obscured in the spectra of the water-saturated samples, the cellulose and lignin absorption features can be identified in reflectance spectra dominated by water (Gao & Goetz, 1994) and wet crop residue can be distinguished from wet soils using CAI (Daughtry, 2001).

Residue covers of corn and soybean scenes are plotted as a function of CAI for water contents ranging from dry to saturated (Fig. 3). For each water content level, residue cover was linearly related to CAI with adjusted r^2 values > 0.95. As water content in the crop residues increased, the slopes of the regression lines also increased (Table 1) and the maximum observed CAI values diminished. Thus, CAI relationships to estimate residue cover for dry conditions would underestimate residue cover for moist conditions. In order to use CAI for assessing crop residue cover over regional scales, a method to correct for varying scene moisture conditions is clearly needed.

The crop residue cover vs. CAI relationships in Fig. 3 represented a wide range of residue cover and water content

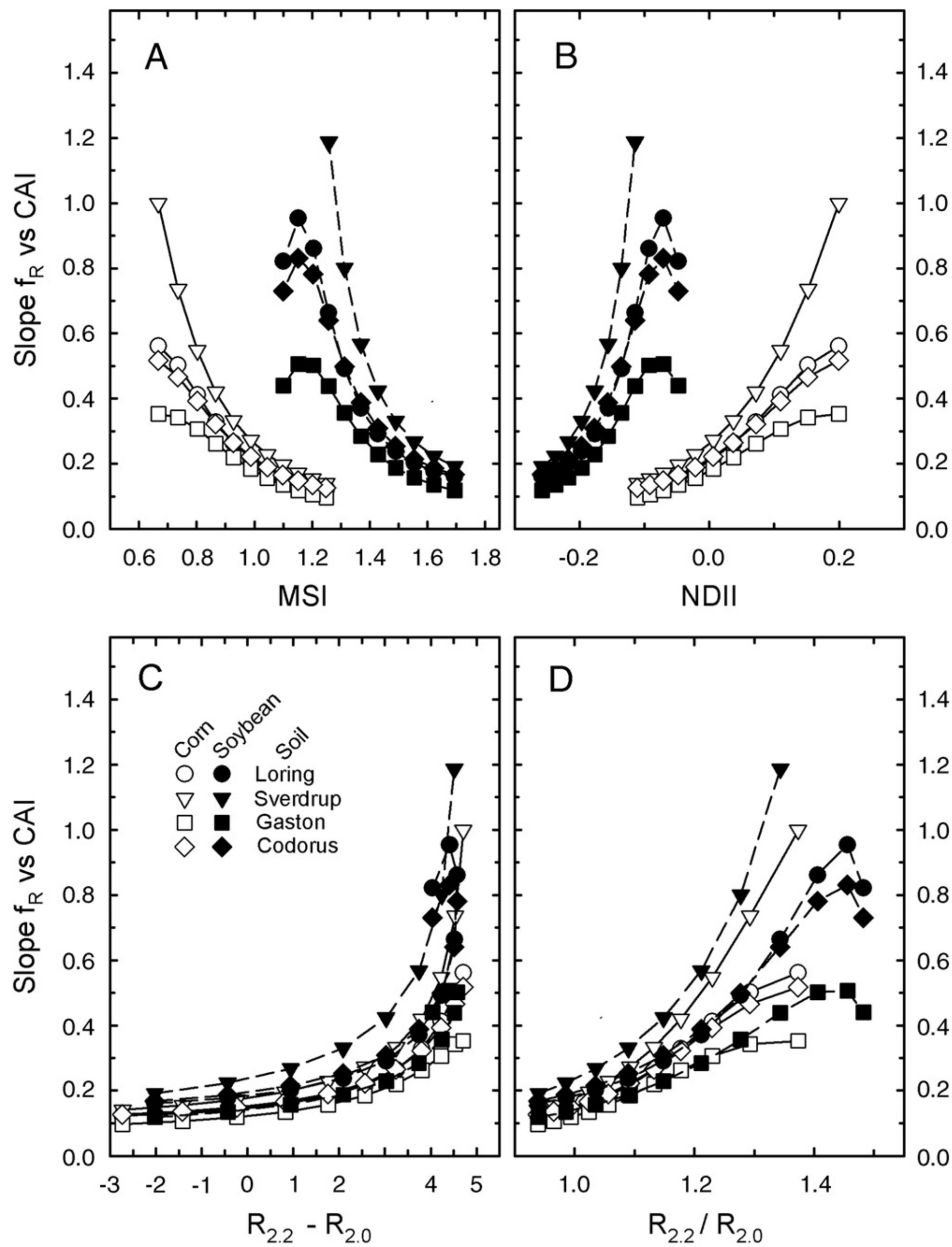

Fig. 10. Slopes of residue cover vs. CAI (slope f_R vs. CAI) for simulated scenes of corn and soybean residues on the four soils plotted as a function of four spectral moisture indices: A) MSI, B) NDII, C) reflectance difference water index ($R_{2.2}-R_{2.0}$), and D) reflectance ratio water index ($R_{2.2}/R_{2.0}$).

conditions for one dry soil. Too many residue covers by soil type by water content level combinations are possible to measure directly. An alternative approach would simulate the reflectance of mixed scenes with various proportions of crop residues and soils using the linear mixture model (Eq. (4)). Although simulated CAI values slightly overestimated the measured CAI values (Fig. 4), the regression model was unbiased, i.e., the average of the estimates taking into account their signs was 0. Thus, the linear mixture model adequately described the overall reflectance for a wide range of residue covers and water content conditions and presented a suitable approach for examining many residue cover by soil type by water content combinations.

3.2. Scene reflectance = f(residue cover, residue water content, soil type, soil water content)

Selected reflectance spectra of four diverse soils with relative water contents ranging from dry to saturated are shown in Fig. 5. Water reduced reflectance of the soils across all wavelengths. The mineral absorption feature near 2200 nm was evident in dry spectrum of each soil but was significantly attenuated as water content increased. These four soils provided representative reflectance spectra profiles (Stoner & Baumgardner, 1981) and a wide range of reflectance values for the mixture models.

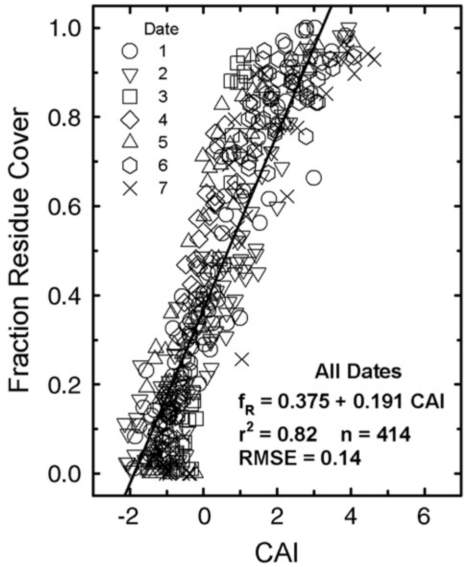

Fig. 11. Residue cover as a function of CAI for corn, soybean, and wheat fields in 2002, 2003, and 2004. The solid line is the overall relationship. Regression coefficients for each date and all dates combined are presented in Table 2.

Reflectance values in five spectral bands are plotted as a function of relative water content for corn residue (Fig. 6A) and Loring soil (Fig. 6B). Regression lines were fitted separately for each band. Similar regression parameters and statistics for the soybean residue and other three soils were obtained, but are not shown. These regression equations were used to estimate reflectance and CAI values for the water contents selected for the scene mixture models. The changes in CAI of the crop residues as relative water content increased are large relative to the changes in CAI of the soils (Fig. 7). Similar relative changes in CAI of dry and wet crop residues and soils have been reported (Nagler et al., 2000). Crop residue water content is the primary transient factor altering the relationship of crop residue cover and CAI in Fig. 3. Weathering and decomposition by soil microbes produce long-term changes in the CAI of crop residues (Daughtry et al., 1996a,b).

Residue covers for simulated scenes of corn residue on Loring soil are plotted as a function of CAI at a range of scene water contents (Fig. 8). The other residue cover by soil type combinations were similar. The slopes of the residue cover vs. CAI for all simulated scenes are shown in Fig. 9. As water content of the residue increased, the slopes increased gradually when RWC < 0.5 and then increased rapidly, particularly for the soybean residue. Thus, an assessment of scene water content is crucial for accurately estimating crop residue cover when moisture conditions may vary from scene to scene or within a scene due to topography. The changes in the slope of the residue cover vs. CAI are plotted for four spectral water indices (Fig. 10). The values of the two spectral indices designed to assess vegetation water content, MSI and NDII, differed for the corn and soybean residues, probably due to differences in water content. Corn residues contained more water per unit of dry matter than the soybean residues at a given RWC (Table 1). However, the difference water index ($R_{2.2}-R_{2.0}$) and the ratio water index ($R_{2.2}/R_{2.0}$) were similar for both residues, an advantage for estimating crop residue covers using remotely sensed data.

As a limited test of the preceding analysis of simulated data, we used reflectance spectra acquired with the spectroradiometer on 7 dates in corn, soybean, and wheat fields in Maryland with various tillage intensities and water contents. Scenes with > 20% green vegetation cover were excluded. Some scenes also included cool season grass residues that had been killed with herbicides prior to no-till planting. For the whole data set, crop residue cover was linearly related to CAI (Fig. 11) with an adjusted r^2 of 0.82 and an RMSE of 0.14. Water contents were measured for only a few soil and residue samples on each date (Table 2). Residue water contents ranged from 0.08 to 1.80 g H_2O/g dry residue while soil water contents ranged from 0.04 to 0.30 g H_2O/g dry soil. When the linear regressions were run for each date separately, the adjusted r^2 increased for 6 of 7 dates and the RMSE decreased for 6 of 7 dates. Although the range of crop residue water contents in the field data set was much less than the simulated data set (Table 1), the slopes of the residue cover vs. CAI for each date are linearly related to the water content of the crop residues (Fig. 12A) and to the reflectance ratio water index for scenes with > 90% residue cover (Fig. 12B). From a practical stand point, it would be difficult to identify which pixels in a scene have > 90% crop residue cover and to assess their water content using the ratio water index without some prior knowledge of the scene. As a pragmatic alternative, we calculated the mean ratio water index for all spectra acquired on each date. The standard deviations of the ratio water index were much larger for all spectra than for the subsets of spectra with > 90% residue cover. Nevertheless, the slope of residue cover vs. CAI was linearly related to the overall mean ratio water index for each date (Fig. 13) which indicated that the changes in crop residue CAI associated with water content changes dominate scene reflectance as expected from Fig. 7.

When the crop residue cover data presented in Fig. 11 were reanalyzed using a multiple linear regression that included the slope and intercept parameters for each date (Table 2), plus the ratio water index and NDVI, the adjusted r^2 increased slightly (Adj. r^2 = 0.88) and the RMSE decreased slightly (0.12). The slope and intercept parameters for each date are related to

Table 2
Regression coefficients for residue cover in corn, soybean, and wheat fields as a function of CAI for each date and all dates combined shown in Fig. 11

Date		n	B_0	B_1	RMSE	Adj. r^2	Residue water g g^{-1}	Soil water g g^{-1}
20 May 2002	1	74	0.377	0.188	0.099	0.896	0.09	na
22 May 2002	2	90	0.334	0.174	0.093	0.888	0.08	0.09
10 June 2003	3	34	0.353	0.477	0.091	0.933	1.80	0.30
1 June 2004	4	35	0.487	0.341	0.089	0.813	1.10	0.28
2 June 2004	5	58	0.434	0.206	0.140	0.834	0.10	0.09
9 June 2004	6	71	0.375	0.203	0.113	0.888	0.11	0.14
30 June 2004	7	46	0.265	0.196	0.165	0.825	0.09	0.04
All		414	0.375	0.191	0.141	0.818	–	–

Residue cover fraction (f_R) was described as $f_R = B_0 + B_1$CAI; where, CAI is the cellulose absorption index and B_0 and B_1 are the linear regression intercept and slope, respectively. RMSE is root mean square error.

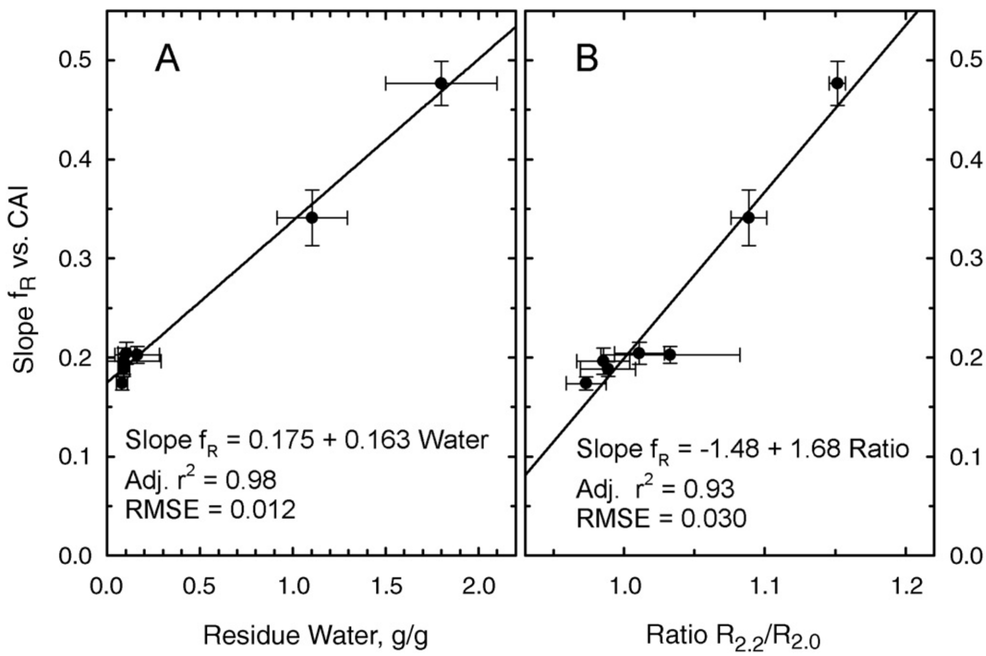

Fig. 12. Slopes of residue cover vs. CAI (slope f_R vs. CAI) from Table 2 as functions of A) crop residue water content and B) crop residue ratio water index ($R_{2.2}/R_{2.0}$) for spectra with > 90% residue cover. Error bars are ± 1 standard deviation.

variations among the 7 dates which are associated with differences in mean crop residue and soil water contents. The other two parameters in the multiple linear regression are associated with scene specific variations, i.e., the ratio water index is related primarily to residue water content (Fig. 7) and the NDVI is related to green vegetation cover. Water in green vegetation reduced CAI values in a similar manner that water reduced the CAI values in crop residues (Daughtry, 2001). This improvement is quite remarkable given that the data were acquired over 3 years with a wide range of residue cover conditions. Some of the remaining unexplained variability in Fig. 11 is probably associated with our protocol for determining residue cover with a dot-grid overlaid on the digital images. The size of the dot-grid relative to the length and width of the crop residue pieces contributed to errors in estimating cover (Bonham, 1989). Expected errors as percentage of true area associated with overlaying 1-mm diameter dots on the digital images to determine the coverage of corn, soybean, and wheat residues ranged from 6 to 35%. Based on the perimeter to area ratios, the errors for scenes that included grass residues or finely shredded crop residues would be even larger.

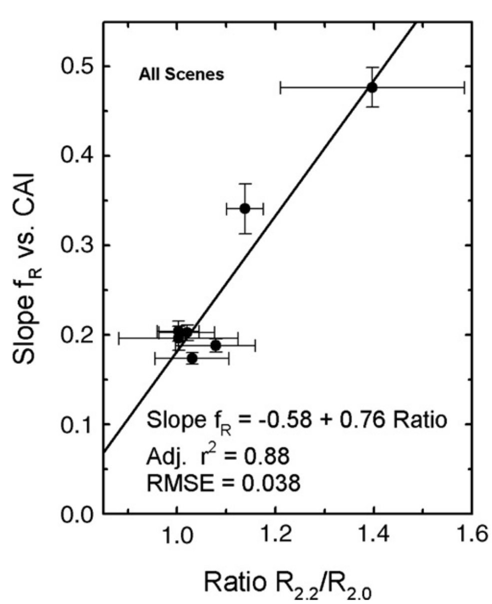

Fig. 13. Slopes of residue cover vs. CAI (slope f_R vs. CAI) as a function of ratio water index ($R_{2.2}/R_{2.0}$) for all spectra on each date. Error bars are ± 1 standard deviation.

4. Summary and conclusions

Crop residue cover is linearly related to the spectral residue cover index, CAI, which is a measure of the relative intensity of the cellulose absorption feature near 2100 nm. However, water in the crop residues and soils significantly attenuated the reflectance signal and altered the slope of the residue cover vs. CAI relationship. Without robust corrections for spatial and temporal variations in scene moisture content, remotely sensed estimates of crop residue cover will be erratic and unreliable. Spectral water indices designed for green vegetation were poorly related to changes in the water contents of the crops residues and soils, which is consistent with other studies.

In a series of laboratory and modeling experiments, we developed a method to adjust crop residue cover estimates based on spectral assessments of relative scene water content and tested it with a limited set of field data. The new ratio water index to improve the predictions of crop residue cover uses the two shortwave infrared bands located on the shoulders of the cellulose absorption feature, $R_{2.0}$ and $R_{2.2}$. Because these two bands are required for calculation of the CAI, there is no need for additional bands. Additional evaluations are needed to refine these spectral indices using aircraft and satellite hyperspectral images over agricultural fields with diverse management practices.

First, these results indicate that current multispectral imaging systems, e.g., Landsat TM or ASTER, will not provide estimates of crop residue cover when soils and residues are wet because the band at 1650 nm was not useful for correction. ASTER has several bands in the shortwave infrared region, but not at 2030 nm wavelength so the correction for soil and residue moisture content cannot be applied. However, hyperspectral data are not required, because the three narrow bands used for both CAI and the correction, could be incorporated into advanced multispectral satellite sensors. Thus, regional surveys of soil tillage practices that affect soil C dynamics may be feasible using either advanced multispectral or hyperspectral remote sensing systems.

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